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SUBSET-SELECTIVITY AND DISTRACTOR MATCHING IN VISUAL CONJUNCTION SEARCH

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Korte samenvatting van:
Subset-selectivity and distractor matching in visual conjunction search
(Subset-selectie en distractor matching in visueel conjunctie-zoeken.)

Drs. N.A. Kaptein en dr.ing. J. Theeuwes

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TNO Technische Menskunde[1], Soesterberg

Management Uittreksel

Bij zoeken naar een conjunctie van kleur en oriëntatie verkregen Theeuwes, Kaptein en Van der Heijden (1993) target absent-responses die in sommige condities sneller en in andere condities langzamer waren dan target present responses. Bovendien waren de hellingen van de zoekfuncties voor target present stimuli vlakker dan voor target absent stimuli. Deze resultaten kunnen niet verklaard worden door de huidige theorieën voor conjunctie-zoeken. Omdat Theeuwes e.a. (1993) in dezelfde studie subset-selectiviteit in conjunctie-zoeken aantoonden, diende de relatie tussen snelle absent responses en subset-selectiviteit te worden bepaald.

Het doel van de huidige studie is te bepalen of snelle absent responses en subset-selectiviteit onafhankelijk kunnen optreden.

Vier experimenten zijn uitgevoerd, waarbij proefpersonen moesten zoeken naar een vooraf omschreven target element tussen een gevarieerd aantal andere (distractor-) elementen. De stimuli werden gedurende 150 ms aangeboden op een beeldscherm, zodat geen gerichte oogbewegingen gemaakt konden worden. Door middel van het indrukken van een toets moest steeds worden aangegeven of de target in het stimulusveld aanwezig was of niet.

De resultaten laten zien dat subset-selectief zoeken onafhankelijk is van het voorkomen van snelle absent responses. Experiment 1 repliceerde de vindingen van Theeuwes e.a. (1993). Experiment 2 liet zien dat de snelle absents niet het resultaat waren van een response bias. De resultaten van Experimenten 3 en 4 lieten zien dat de snelle absents kunnen worden verklaard door een zwak parallel "distractor matching"-proces dat het mogelijk maakt "target absent" te responderen als alle relevante distractoren voldoende op elkaar lijken. Omdat dit proces gemakkelijk verstoord kan worden, kan het niet ontvangen van zo'n "gelijkheids"-signaal niet worden gebruikt voor de "target present"-beslissing. Betoogd wordt dat subset-selectief zoeken en distractor matching waarschijnlijk in andere conjunctie-zoek experimenten ook plaatsgevonden hebben.

[1] Per 1 februari 1994 is de naam Instituut voor Zintuigfysiologie TNO gewijzigd in TNO Technische Menskunde.

CONTENTS Page

SUMMARY 5

SAMENVATTING 6

1 INTRODUCTION 7

2 EXPERIMENT 1 9
- 2.1 Method 10
- 2.2 Results 12
- 2.3 Discussion 17

3 EXPERIMENT 2 19
- 3.1 Method 19
- 3.2 Results 20
- 3.3 Discussion: Target search and distractor matching 25

4 EXPERIMENT 3 27
- 4.1 Method 27
- 4.2 Results 28
- 4.3 Discussion 34

5 EXPERIMENT 4 35
- 5.1 Method 35
- 5.2 Results 37
- 5.3 Discussion 42

6 GENERAL DISCUSSION 43

REFERENCES 46

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SUMMARY

In search for a conjunction of color and *orientation*, Theeuwes, Kaptein and Van der Heijden (1993) obtained target absent responses that were in some conditions faster and in other conditions slower than target present responses. In addition, target absent search function slopes were shallower than target present slopes. These findings cannot be explained by present conjunction search theories. Since in the same study Theeuwes et al. demonstrated subset-selectivity in conjunction search, the interdependence of the fast absent responses and subset-selective search needed to be assessed. The present study shows that subset-selective search is independent of the occurrence of fast absent responses. Experiment 1 replicated the findings of Theeuwes et al. (1993). Experiment 2 showed that the fast absents were not the result of a response bias. The results of Experiments 3 and 4 showed that the fast absents can be explained by a weak, parallel distractor matching process that enables responding "target absent" if all relevant distractor elements are similar. Since this process is easily disturbed, the absence of a "sameness"-signal can not be used for "target present"-decisions. It is argued that both subset-selective search and distractor matching may have unnotedly occurred in previously reported experiments.

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TNO Technische Menskunde[1]
Soesterberg

Subset-selectie en distractor matching in visueel conjunctie-zoeken

N.A. Kaptein en J. Theeuwes

SAMENVATTING

Bij zoeken naar een conjunctie van kleur en oriëntatie verkregen Theeuwes, Kaptein en Van der Heijden (1993) target absent-responses die in sommige condities sneller en in andere condities langzamer waren dan target present responses. Bovendien waren de hellingen van de zoekfuncties voor target present stimuli vlakker dan voor target absent stimuli. Deze resultaten kunnen niet verklaard worden door de huidige theorieën voor conjunctie-zoeken. Omdat Theeuwes e.a. (1993) in dezelfde studie subset-selectiviteit in conjunctie-zoeken aantoonden, diende de relatie tussen snelle absent responses en subset-selectiviteit te worden bepaald. De huidige studie laat zien dat subset-selectief zoeken onafhankelijk is van het voorkomen van snelle absent responses. Experiment 1 repliceerde de vindingen van Theeuwes e.a. (1993). Experiment 2 liet zien dat de snelle absents niet het resultaat waren van een response bias. De resultaten van Experimenten 3 en 4 lieten zien dat de snelle absents kunnen worden verklaard door een zwak parallel "distractor matching"-proces dat het mogelijk maakt "target absent" te responderen als alle relevante distractoren voldoende op elkaar lijken. Omdat dit proces gemakkelijk verstoord kan worden, kan het niet ontvangen van zo'n "gelijkheids"-signaal niet worden gebruikt voor de "target present"-beslissing. Betoogd wordt dat subset-selectief zoeken en distractor matching waarschijnlijk in andere conjunctie-zoek experimenten ook plaatsgevonden hebben.

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1 INTRODUCTION

In a typical visual search task subjects search for a prespecified target element among a varying number of distractor elements, and have to indicate trial by trial whether that target element is present in the stimulus display or whether it is not. Consequently, a model of search performance should be able to account for both target present and target absent results. Nevertheless, most explanations of search performance are primarily based on the results of target present trials. Only when target-absent results are in line with theory they are used as additional support. Target absent results that are not explicitly predicted by the theory are taken to reflect strategies that are used for deciding that a target is absent. As a consequence, as long as absent results are not clearly at odds with the theory, deviations from theoretical predictions do not lead to adjustment of the theory. In the following sections the basic rationale of most visual search theories is set out, followed by an overview of target absent findings in conjunction search that actually *are* at odds with all available search theories. The present study is aimed at exploring and explaining these findings.

In visual search, a fundamental distinction is made between feature search and conjunction search (Treisman & Gelade, 1980). In feature search the target is unique within one dimension. For instance, the target is a red item among green ones, or a vertical bar among horizontal bars. Reaction Times (RTs) for target present trials in feature search are independent of the number of distractor elements. As long as target and distractor are easily discriminable, the target is said tot 'pop out' and is always found immediately. In conjunction search the target is also unique, but not within one single dimension. For instance, the target may be a red vertical bar among red horizontal and green vertical bars, or a small X among large Xs and small Os. In conjunction search target present RTs increase with the number of distractor elements (e.g., Treisman & Gelade, 1980; Treisman, 1988; Duncan & Humphreys, 1989; Carter, 1982). Nothing pops out and serial search is required to find the target. Visual search results generally fit in one of these two classes.

Like target present results, target absent results in many cases are consistently predicted by the standard theories of feature and conjunction search. In feature search both for target present and absent trials flat search functions are obtained. Note that the intercepts of the absent functions are generally higher. Subjects are thought to wait for the popping-out of the target to respond 'present' and by default respond 'absent' in case such a pop-out does not occur. As regards conjunction search, many target present and absent findings are consistent with the notion of serial self-terminating search. When searching, for example, for a green T among brown Ts and green Xs Treisman and Gelade (1980) found slopes of target absent search functions that were approximately twice as large as the slopes of the corresponding target present functions. This finding, the 1:2 ratio of target present and target absent slopes, is compatible with the notion of serial, self-terminating search. When subjects search the

stimulus display *until* the target is found it is expected that the number of elements that have to be searched is twice as large in target absent trials compared to target present trials. Note that in target absent trials all elements have to be searched. If RTs then are plotted against display size (the number of elements in the display) search function slopes for target absent trials should be twice as large. Similar findings have been reported by others (e.g., Quinlan & Humphreys, 1987; Egeth, Virzi & Garbart, 1984; Treisman, 1991).

Both of these two patterns of results, typical for feature search and conjunction search, are perfectly in line with a one-process account of the results of target present and target absent data. One single search process, whether it is parallel feature search or serial self-terminating conjunction search, can be used to explain both target present and target absent data. However, it has been questioned whether the serial self-terminating search process alone is sufficient to explain conjunction search behavior (Pashler, 1987; Houck & Hoffman, 1986). The starting point of this position was the observation that in some conjunction search tasks the ratio of target present and target absent slopes was approximately 1:1 instead of the usual 1:2 ratio (e.g., Houck & Hoffman, 1986; Pashler, 1987; Duncan & Humphreys, 1989: experiment 3). Note that these results were obtained with rather small display sizes.

Such a 1:1 ratio of target present and target absent slopes was also obtained by Theeuwes, Kaptein and Van der Heijden (1993) in a conjunction search task. Their task was to search for a red, vertical target among green vertical and red tilted distractors. Yet, Theeuwes et al. independently varied the numbers of red and green distractor elements. In line with a claim of Egeth et al. (1984), Theeuwes et al. found selective search among elements in the color of the target. Thus, elements were first segregated on the basis of their color and subsequently the elements in the target color were analyzed as to their orientation. In apparent contradiction with other results, if only the effect of the number of elements in the target color was considered target absent slopes were shallower than target present slopes. On the other hand, if only the effect of the number of green elements was considered target absent slopes were steeper. As a consequence, if only trials with an equal number of red and green elements were taken into account, target present and target absent slopes were equal, similar to the results of Houck & Hoffman (1986) and Pashler (1987). These findings show that the diagnostic of Theeuwes et al. (independently varying the numbers of elements of the two distractor types) reveals aspects of conjunction search processes that remain uncovered with the traditional methodology (covarying the numbers of both distractor types). In this light, another result of Theeuwes et al. (1993) seems noteworthy. Though in some conditions (e.g., with 6 green and 1 red element or 6 green and 4 red elements) target present responses were faster than target absent responses, in other conditions (e.g., 4 green and 6 red elements or 2 green and 4 red elements) target absent results were faster. This type of result can not be explained with a one-process serial self-terminating search model. Again, these findings would not have been obtained when only

2.1 Method

Subjects

Eight right-handed subjects, ranging in age from 19 to 23 years, participated as paid volunteers.

Apparatus

A SX-386 personal computer (G2) with a NEC Multisync 3D VGA color screen (resolution 640 × 350; very rapid phosphor decay: 0.64 ms after display offset light emission is only half of its maximum value) controlled the stimulus presentations and the timing of the events and recorded RTs through Micro Experimental Laboratory software (Schneider, 1988). The '/'-key and the 'z'-key of the computer keyboard were used as response buttons. Subjects were tested in a sound attenuated, dimly lit room with their heads resting on a chinrest adjusted to a comfortable height. The CRT was located at eye level, 97 cm from the chinrest.

Task

Subjects were instructed to determine as fast as possible, without making too many errors, whether a red vertical bar (the target) was present in the stimulus field. Half of the subjects had to respond 'target present' by pressing the 'z'-key and 'target absent' by pressing the '/'-key, and half of the subjects responded 'target present' by pressing the '/'-key and 'target absent' by pressing the 'z'-key.

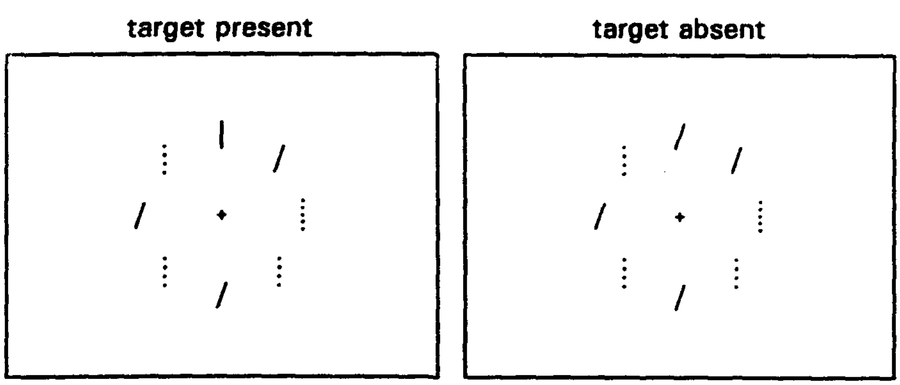

Fig. 1 Examples of stimulus displays used in Experiment 1, both with a target present (left panel) and absent (right panel). Red line segments are solid, green ones dotted.

Stimuli

Fig. 1 shows examples of stimulus displays, both with (left) and without a target (right). In target-absent trials the stimulus field consisted of a fixation dot (0.3°),

stimulus displays with equal numbers of different types of distractors would have been used. This observation may indicate that similar effects might have played a role in traditional search tasks. Yet, because in these tasks the numbers of distractors never were varied independently these effects could not show up.

No one-process model can explain that in some conditions target present responses are faster, while in other conditions target absent results are faster. Therefore, these results suggest that different search processes were used to respond to target present trials and to target absent trials, which is not in line with any theory of conjunction search. Yet, the generality of the target absent findings of Theeuwes et al. (1993) might be questioned. They reported the evidence for subset selective search together with the extraordinary target absent results. Both the selectivity and the fast absents are potentially important for visual search theory. For that reason the generality and interdependence of these findings needed to be assessed.

The present study was primarily designed to verify the findings of Theeuwes et al. (1993), and to explain their fast absent results in terms of a two-process theory of target absent behavior in conjunction search. A second goal is to show that subset-selective search and fast absent responding are not interdependent, and do not both reflect some unknown experimental or theoretical artifact.

First the findings of Theeuwes et al. (1993) were replicated (Experiment 1). In a subsequent experiment (Experiment 2) it was investigated whether a response bias could explain these results. To account for the observed findings a model of target absent behavior is proposed, that was tested in Experiments 3 and 4. In these latter two experiments it was attempted to obtain subset selective search with a 1:2 ratio of target present and target absent slopes.

2 EXPERIMENT 1

Experiment 1 was performed to replicate the findings of Experiment 1 of Theeuwes et al. (1993). The method was identical to that of Theeuwes et al., except that in the present experiment equiluminant red and green stimuli were used. In the present experiment subjects had to search for a red vertical target among green vertical and red 20° tilted distractors. It was expected that, as in Theeuwes et al., search latencies for target present trials would increase with the number of red elements, and not with the number of green elements.

1, 2, 4 or 6 red 0.6° line segments, tilted 20° clockwise and 1, 2, 4 or 6 green vertical 0.6° line segments. In target-present trials one of the red tilted line segments was replaced by a red vertical line segment: the target. In all trials stimuli were randomly distributed equally spaced on an imaginary circle whose radius was 3.0° of visual angle. As a consequence the stimuli were separated at least 1.5° of visual angle, which is sufficient to prevent lateral masking effects (see, e.g., Cohen & Ivry, 1989, 1991). All stimuli were presented at the same distance from the fixation point, to control for differential retinal processing capacities.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of, respectively, .28/.36 and a luminance of 40 cd/m^2). The target and the distractors were presented in nominally equiluminant (9.3 cd/m^2) red (.63/.36) and green (.31/.60). The background was dark grey (.32/.37; 0.2 cd/m^2). All color characteristics were measured with a Photoresearch PR-703A spectrophotometer.

Procedure

A block of trials consisted of 4 (1, 2, 4 or 6 red items) × 4 (1, 2, 4 or 6 green items) × 2 (target present or target absent) × 10 (replicas) = 320 trials. Each subject received four blocks of stimuli, that is a total of 1280 experimental trials. Before the first experimental block subjects run two practice blocks (each consisting of 320 trials, with feedback about the percentage of errors and mean RT on the preceding trials every 40 trials). There was a 10 minutes break between the blocks. Subsequently, each subject was presented with four experimental blocks, with a 20 minute break after two blocks. Subjects were provided with the opportunity for a break every 80 trials, when subjects received feedback about their performance (percentage of errors and mean RT) on the preceding trials. Subjects were instructed to respond as fast as possible, without making too many errors. Each block took approximately 10 minutes.

All trials started with the presentation of a fixation dot. After 700 ms the stimulus field was projected on the screen for 150 ms, an exposure duration too short to make directed eye-movements. If no response was given after 2000 ms or if the response was incorrect subjects were informed by means of a warning beep that they had committed an error. It was emphasized that subjects should not move their eyes during the course of a trial. It was stressed that a steady fixation would reduce RT and make the task easier.

2.2 Results

Respor·͜ times longer than 1,000 ms were counted as errors, which led to a loss of 1.88% of the trials. These responses were not included in the error analyses, because errors were analyzed to control for speed-accuracy trade-offs. If slow responses were included in the error analyses, they would mask trade-off effects.

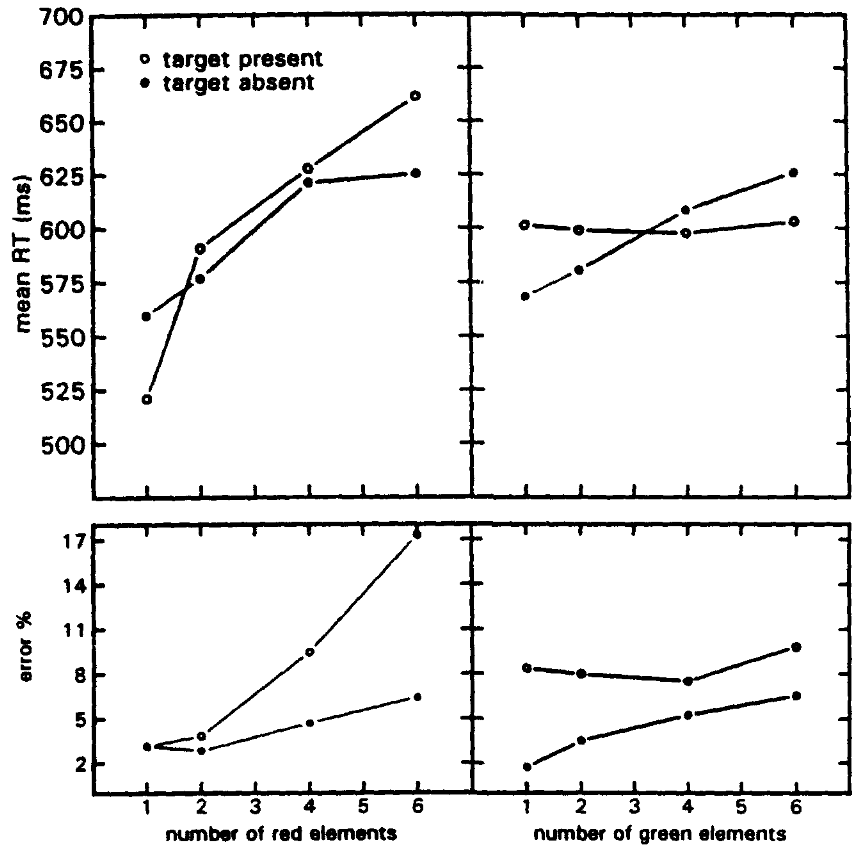

Fig. 2 Experiment 1: Mean RTs and error percentages for target present and target absent trials, as a function of the number of displayed red elements (Panel A) and of the number of green elements (Panel B).

In Fig. 2 mean RTs and error percentages are plotted against the number of displayed red elements (Panel A), separately for target present trials and target absent trials. The same data are also plotted against the number of green elements (Panel B).

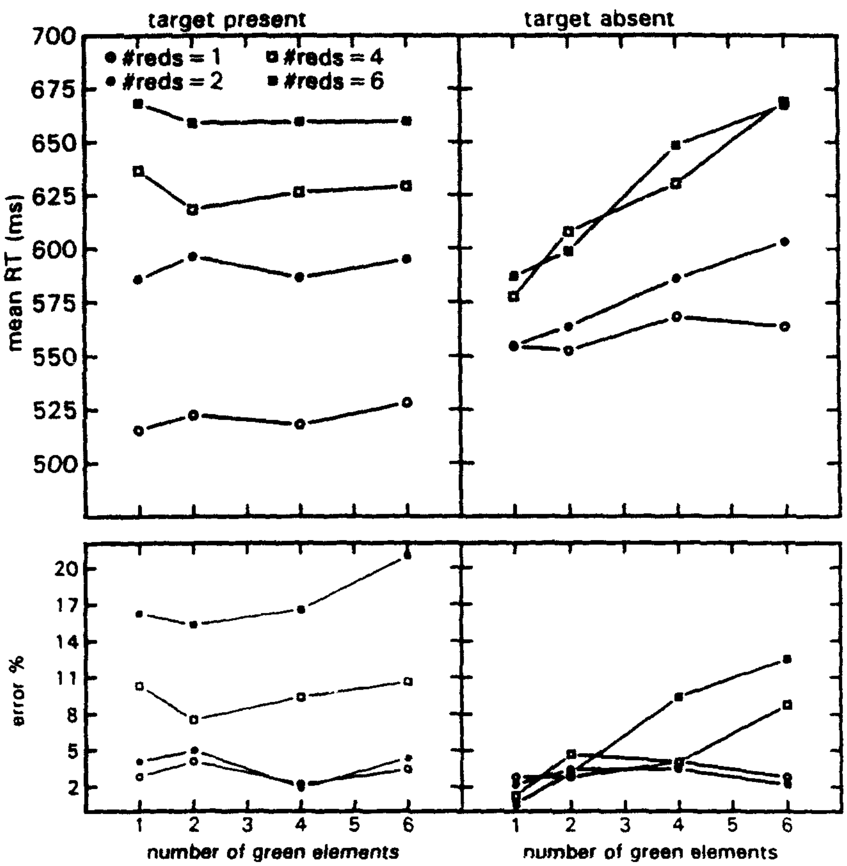

Fig. 3 Experiment 1: Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

In Fig. 3 mean RTs and error percentages are plotted against the number of displayed green elements, separately for each number of red elements, both for target present (Panel A) and target absent trials (Panel B).

Subjects' mean RTs for target absent and target present trials were submitted to separate ANOVAs, with the number of reds (1, 2, 4 and 6) and the number of greens (1, 2, 4 and 6) as main factors. For target present trials there was a significant main effect on RT of the number of red elements [$F(3,21) = 83.1$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was also not significant. For target absent trials, there was a significant main effect of the number of green items [$F(3,21) = 70.6$, $p < 0.01$] and of the number oi red items [$F(3,21) = 56.2$, $p < 0.01$]. The interaction between the numbers of red and green elements was also significant [$F(9,63) = 6.49$, $p < 0.01$].

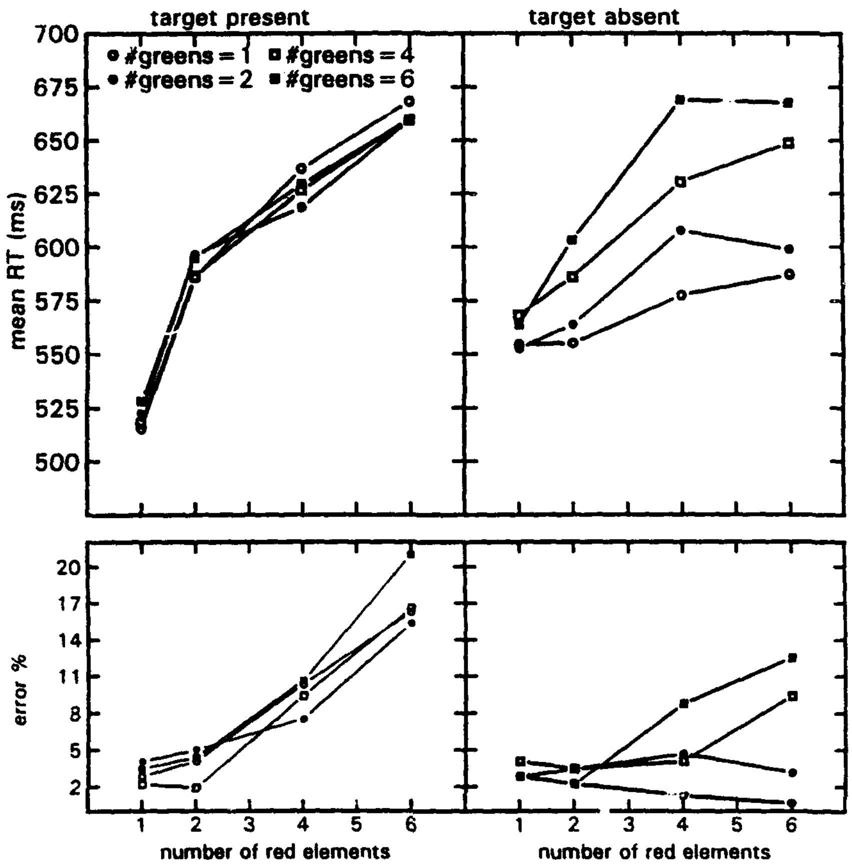

Fig. 4 Experiment 1: Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

In Fig. 4 the data of Fig. 3 are represented in a different way. Mean RTs and error percentages are plotted against the number of red elements, separately for each number of green elements, both for target present (panel A) and for target absent trials (Panel B).

To determine the slopes of the RT functions presented in Figs 2, 3 and 4, linear regression analyses were performed on the mean RTs per subject. The mean slopes and intercepts are shown in Table I. T-tests were performed to test whether the slopes were significantly different from zero. The results of these tests are shown in Table I as well.

Table I Slopes and intercepts corresponding to the RT functions in Figs 2 to 4.

	intercept [ms]	slope [ms/ element]	t-value	p <
RT as a function of # green elements (see Fig. 2)				
target present	599.3	0.3	0.342	n.s.
target absent	557.8	11.7	12.833	0.01
RT as a function of # red elements (see Fig. 2)				
target present	516.6	25.7	10.444	0.01
target absent	550.5	13.9	10.024	0.01
RT as a function of # green elements, separately for each # reds (see Fig. 3)				
target present				
1 red element	514.7	1.9	1.623	n.s.
2 red elements	588.1	0.9	0.435	n.s.
4 red elements	628.7	-0.3	0.127	n.s.
6 red elements	665.5	-1.2	0.523	n.s.
target absent				
1 red element	551.2	2.6	2.917	0.05
2 red elements	544.9	9.8	4.661	0.01
4 red elements	565.3	17.2	7.796	0.01
6 red elements	569.6	17.1	7.830	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 4)				
target present				
1 green element	512.6	26.4	6.614	0.01
2 green elements	520.9	24.1	7.104	0.01
4 green elements	512.6	26.1	9.795	0.01
6 green elements	524.9	24.0	9.196	0.01
target absent				
1 green element	545.0	7.2	3.337	0.01
2 green elements	546.6	10.5	5.822	0.01
4 green elements	554.1	16.7	6.131	0.01
6 green elements	556.4	21.4	11.883	0.01

To achieve homogeneity of the error rate variance, the mean error rates per cell (i.e., per combination of subject, trial type, number of red elements and number of green elements), were transformed by means of an arcsine transformation before the error rates were submitted to the ANOVAs.

Error rates for target present and target absent trials were submitted to separate ANOVAs, with number of reds (1, 2, 4 and 6) and number of greens (1, 2, 4 and 6) as main factors. For target present trials there was a significant main effect on error rate of the number of red elements [$F(3,21) = 38.5$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was also not significant. The error rate increased with the number of red elements and not with the number of green elements. For target absent trials there were main effects on error rate of the number of green elements [$F(3,21) = 8.2$, $p < 0.01$], but not of the number of red elements. The interaction between the numbers of red and green elements was significant as well [$F(9,63) = 3.5$, $p < 0.01$].

Since all significant effects on error rate mimic effects on response latency, the significance of effects on RT can not be the result of a speed accuracy trade-off.

All results were very similar to the results of Experiment 1 of Theeuwes et al. (1993). As in Theeuwes et al. (1993), in the present experiment the relative contribution of separate distractor types to search function slopes is investigated by independently varying their numbers. In standard conjunction search experiments (e.g. Treisman, Sykes & Gelade, 1977; Treisman & Gelade, 1980; Duncan & Humphreys, 1989; Wolfe, Cave & Franzel, 1989), half of the distractors is of one type (e.g. red tilted), and the other half of the second type (green vertical). To compare the present results with previous conjunction search experiments, only trials with an equal number of red and green items should be considered.

In traditional conjunction search experiments, there is always an equal number of different distractor types. In order to compare the present data with the results of these conjunction search experiments, mean RTs and errors were calculated for those conditions in which there was an equal number of elements of both distractor types. Fig. 5 gives these results. To determine the slopes of both the target present and the target absent RT functions, the individual mean RTs were submitted to a linear regression analysis. Of the target present function the intercept was 516, and the slope was 12.8 ms/element [which was significantly different from zero: $t(7) = 2.849$, $p < 0.05$]; of the target absent function the intercept was 525 ms, and the slope was 12.3 ms/element [$t(7) = 3.739$, $p < 0.01$]. So for this subset of trials, RTs increase with display size with comparable significant slopes for target present and absent trials.

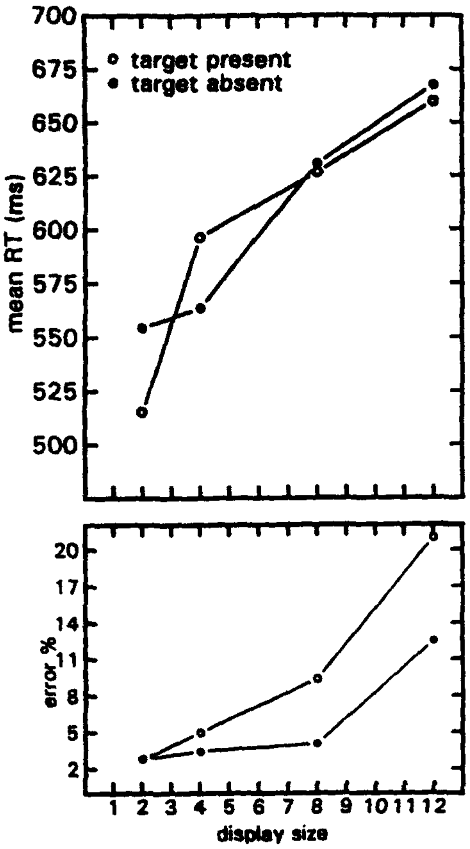

Fig. 5 Experiment 1: Mean RTs and error percentages of trials with an equal number of red and green elements, as a function of the display size, both for target present and for target absent trials.

2.3 Discussion

The results of the present Experiment 1 perfectly replicate the findings of Theeuwes et al. (1993). Ratio of target present and target absent slopes (with only equal nu.nbers of red and green elements considered) is approximately equal to 1:1, as was found by Theeuwes et al. (1993) and which is in line with the results of Pashler (1987) and Houck & Hoffman (1986). Again, the present results showed that this observation is a to some degree artificial finding due to the choice of stimuli, since the pattern of results was different when considering all conditions so that the effects of the numbers of red and green elements could be assessed separately. The effect of the number of red elements was larger for target present responses, the effect of the number of green elements was larger for target absent responses, so that a 1:1 slope only is found when equal numbers of red and green elements are considered. The present methodology, independently varying the numbers of red and green elements, showed that in some conditions target absent responses were slower than target present responses, whereas in other conditions target absent responses were faster. As stated in the Introduction, this pattern of results contradicts any one-process search-default account.

At this stage it should be noted that the result that in some conditions present responses are faster while in other conditions absents are faster, may reflect an experimental artifact. If subjects were biased, either towards responding 'target present', or towards responding 'target absent', the absolute level of response latencies of one of the trial types might become relatively low. Without such a bias, RTs to either present or absent trials might be in all conditions faster than RTs on trials of the other type. Error scores would hint towards such a bias. A closer look at the results of Experiment 1 (as well as at the results of Theeuwes et al., 1993) suggests that this artifact may have occurred. On target present trials subjects have, on the average, made more errors than on target absent trials. This finding may be interpreted in two ways: 1. Subjects sometimes simply miss the target and therefore respond 'absent'. 2. Subjects are biased towards responding 'target absent'.

Experiment 2 was performed in order to find out whether a possible response bias may have caused or affected the results of Experiment 1. A response bias, as well as other response competition effects (see, e.g., Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979), can only occur when at least two possible responses are required. These problems have been addressed by using a 'go-no go'-task instead of a 'yes-no'-task (Van der Heijden & La Heij, 1982; Van der Heijden, La Heij & Boer, 1983; Egeth, Folk & Mullin, 1985). Typically, in a go-no go task, subjects are to respond if a target is present, and to refrain from responding if it is not, whereas in a yes-no task subjects are to push different buttons in different conditions. Van der Heijden & La Heij (1982) compared simple visual search performance on a yes-no task with performance on a go-no go task, using physically identical stimuli. With the yes-no task they found more effect of practice (on search function slopes), more errors and higher intercept values than with the go-no go task. Van der Heijden & La Heij only compared target present trials (except for the error rate comparison) because no RTs were available for 'no go'-trials. Their findings indicated that the results of a go-no go task are less easily affected by irrelevant factors than a yes-no task.

Experiment 2 is a replication of Experiment 1, this time with a go-no go procedure. Since in the present study both target present and target absent data are of importance, the go-no go task was used both with the instruction to respond on target present trials and to refrain from responding on target absent trials, and with the instruction to respond on target absent trials and to refrain from responding on target present trials. This latter factor was a between-subjects variable.

3 EXPERIMENT 2

In Experiment 2 the same stimuli were presented as in Experiment 1. However, in the present experiment a 'go-no go' task was used. Half of the subjects responded on target present trials, and refrained from responding on target absent trials. The other half of the subjects responded on target absent trials, and refrained from responding on target present trials. In this way can be determined to what extent the results of Experiment 1, and indirectly also the results of Theeuwes et al. (1993) reflect purely perceptual processes, and on the other hand to what extent results were affected by response competition processes, or by interference between target search and distractor matching.

It was expected that on the average RTs would be faster than in Experiment 1 (because of the lack of response competition). It was also expected that target absent response latencies would decrease less than target present results, since the results of Experiment 1 may partially reflect a bias in favor of absent-responses.

3.1 **Method**

Subjects

Sixteen right-handed subjects, ranging in age from 21 to 33 years participated as paid volunteers.

Apparatus

The apparatus was similar to that in Experiment 1.

Task and stimuli

In the present experiment a 'go-no go' task was used instead of a 'yes-no' task. Half of the subjects had to respond by pressing the space bar when a target was present, and to refrain from responding when no target was present. The other half of the subjects had to refrain from responding when a target was present, and to respond by pressing the space bar when no target was present. Other aspects of task and stimuli were similar as in Experiment 1.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of, respectively, .28/.31 and a luminance of 30 cd/m^2). The target and the distractors were presented in equiluminant (8.6 cd/m^2) red (.62/.36) and green (.31/.60), with a dark grey background (.32/.367; 0.3 cd/m^2).

Procedure

The procedure was analogous to the procedure in Experiment 1. Separate error feedback was generated for misses and false alarms. In the present experiment, if no response was given after 1000 ms or if the response was incorrect, subjects were informed by means of a warning beep when they had committed an error.

3.2 Results

Response times longer than 900 ms were counted as errors, which led to a loss of 0.79% of the go-trials.

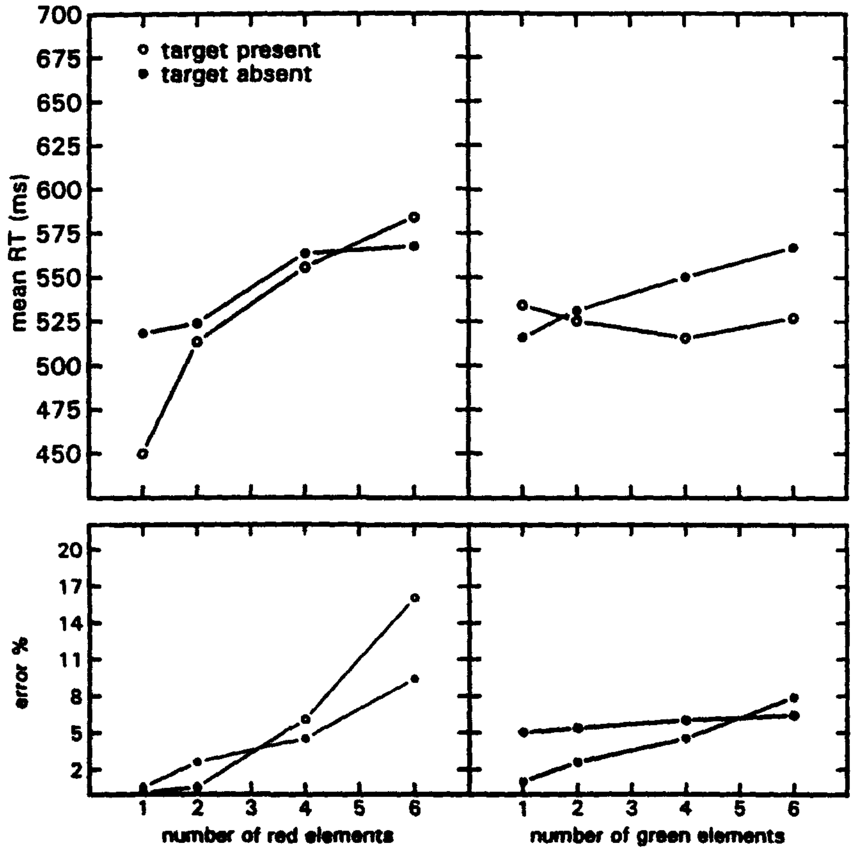

Fig. 6 Experiment 2: Mean RTs and error percentages for target present and target absent trials, as a function of the number of displayed red elements (Panel A) and of the number of green elements (Panel B).

In Fig. 6 mean RTs and error percentages are plotted against the number of displayed green elements (Panel A) and against the number of red elements (Panel B), separately for target present and target absent trials.

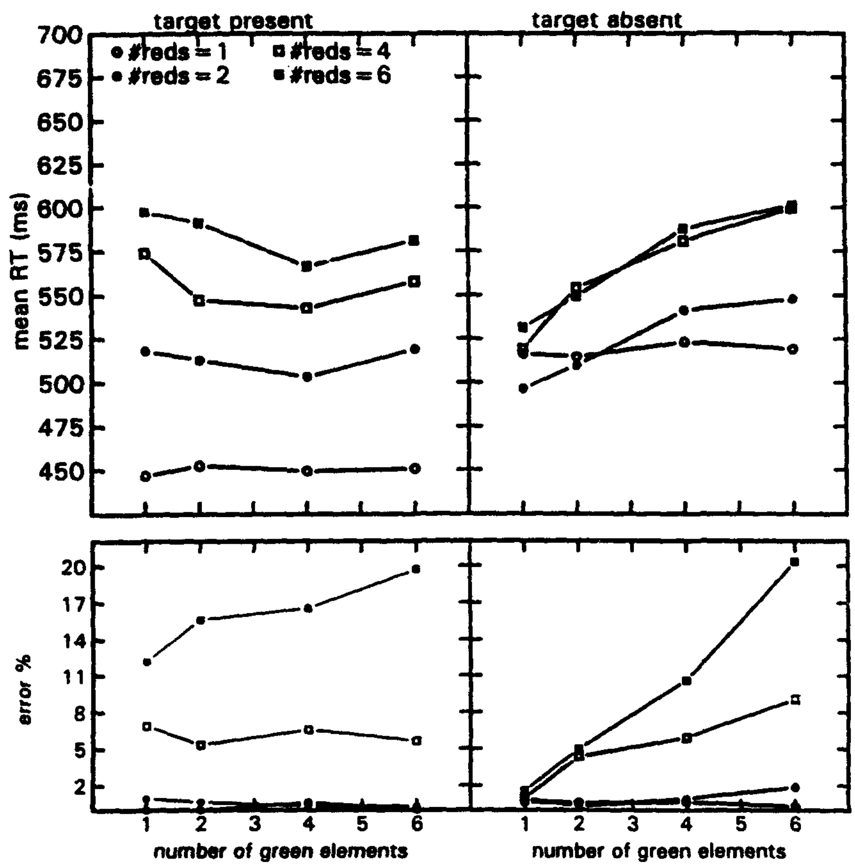

Fig. 7 Experiment 2: Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

In Fig. 7 mean RTs and error percentages are plotted against the number of displayed green elements, separately for each number of red elements, both for target present (Panel A) and for target absent go-trials (Panel B). Note that Panel A and B represent RTs of different groups of subjects, because trial type is a between-subjects variable as a consequence of the go-no go task that was used.

For target present trials, there was a significant main effect on RT of both the number of red elements [$F(3,21) = 100.1$, $p < 0.01$] and of the number of green elements [$F(3,21) = 7.51$, $p < 0.01$]. The interaction between the numbers of red and green elements was also significant [$F(9,63) = 4.44$, $p < 0.01$]. For target absent trials, there was a significant main effect on RT of the number of red items [$F(3,21) = 2.1 \cdot 10^4$, $p < 0.01$] and of the number of green items [$F(3,21) =$ 70.0, $p < 0.01$]. The interaction between the number of red and green elements was also significant [$F(9,63) = 9.91$, $p < 0.01$].

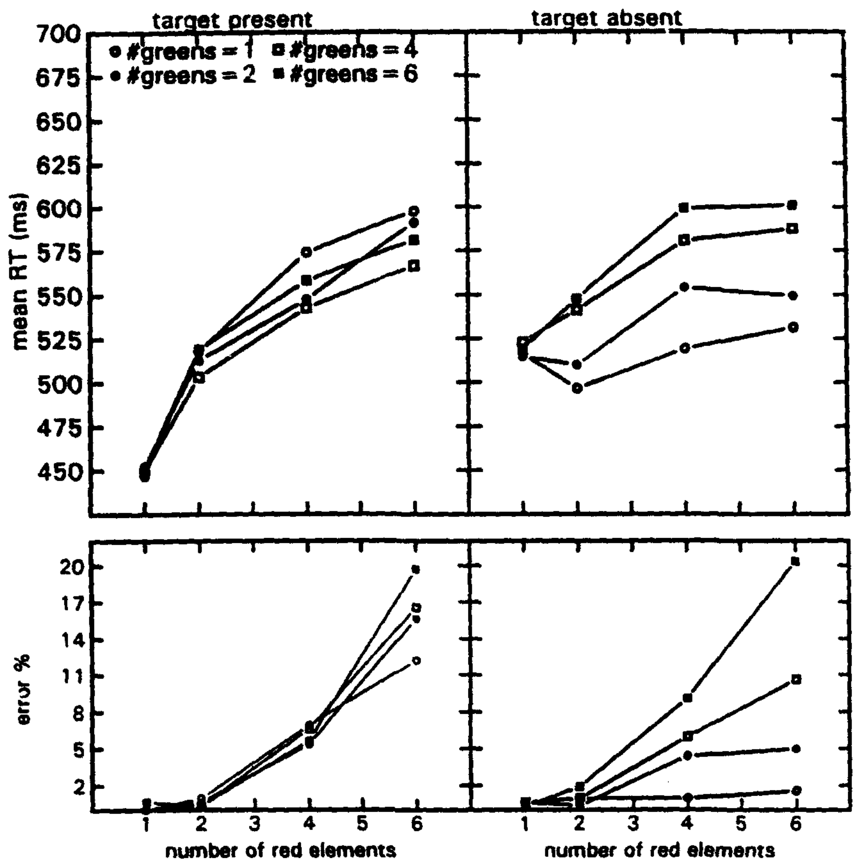

Fig. 8 Experiment 2: Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

In Fig. 8 the data in Fig. 7 are represented in an different way. In Fig. 8 mean RTs and error percentages are plotted against the number of red elements, separately for each number of green elements, both for target present (Panel A) and for target absent trials (Panel B).

To determine the slopes of the RT functions, the individual mean RTs were submitted to a linear regression analysis. The slopes corresponding to the RT functions in Figs 6 to 8 are shown in Table II. The results of the T-tests are shown in Table II as well.

T^able II Slopes and intercepts corresponding to the RT functions in Figs 6 to 8.

	intercept [ms]	slope [ms/element]	t-value	p <
RT as a function of # green elements (see Fig. 6)				
target present	534.2	-3.4	1.620	n.s.
target absent	496.1	12.8	6.312	0.01
RT as a function of # red elements (see Fig. 6)				
target present	439.2	25.8	10.045	0.01
target absent	499.1	11.9	4.734	0.01
RT as a function of # green elements, separately for each # reds (see Fig. 7)				
target present				
1 red element	447.9	0.5	0.580	n.s.
2 red elements	513.6	-0.1	0.082	n.s.
4 red elements	562.5	-2.6	1.735	n.s.
6 red elements	605.0	-5.8	2.240	0.05
target absent				
1 red element	514.3	1.1	0.762	n.s.
2 red elements	488.9	10.7	11.554	0.01
4 red elements	513.9	15.9	11.215	0.01
6 red elements	513.1	15.8	8.606	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 8)				
target present				
1 green element	440.5	28.7	12.878	0.01
2 green elements	443.1	25.5	8.951	0.01
4 green elements	443.1	22.1	10.172	0.01
6 green elements	442.2	25.3	9.831	0.01
target absent				
1 green element	500.0	4.8	2.068	0.05
2 green elements	503.1	8.8	3.238	0.01
4 green elements	507.8	14.4	5.481	0.01
6 green elements	511.8	17.0	8.289	0.01

For target present trials there was a significant main effect on error rate of the number of red elements [$F(3,21) = 104$, $p < 0.01$], but not of the number of green elements. Also the interaction between the numbers of red and green elements was not significant. As the number of red elements had an effect on error rate, it is not meaningful to determine the degree of linearity of the search function. For target absent trials there were main effects on error rate both of

the number of red elements [$F(3,21) = 16.2$, $p < 0.01$] and of the number of green elements [$F(3,21) = 19.1$, $p < 0.01$]. The interaction between the numbers of red and green elements was significant as well [$F(9,63) = 7.90$, $p < 0.01$].

In Experiment 1 subjects made more errors on target present trials than on target absent trials. The 'yes-no'-paradigm that was used did not offer a possibility to discriminate between a bias towards responding 'target absent', or the occasional missing of the target. The present 'go-no go'-paradigm does. A bias towards 'go' or 'no go' is independent of whether the response is coupled to target present or to target absent trials. If the target is missed occasionally, subjects show more misses (failures to respond) on target present go responses and relatively more false alarms (failures to refrain from responding) on target absent go responses.

Subjects who had to 'go' when the target was present, missed their response on 5.7% of the trials target present trials, and gave a false alarm on 7.5% of the target absent trials. On the other hand, subjects that had to 'go' when the target was absent, missed on 3.4% of the trials and gave a false alarm on 6.2% of the trials. Thus, subjects appear to be biased to respond instead of refraining from responding in both types of trial.

In Experiment 1 more errors were made on target present trials, suggesting a bias towards responding 'target absent'. The present results showed a bias as well, but the analysis above showed that the bias was in response readiness and not in a tendency towards responding 'target present' or 'target absent'. Subjects were more likely to respond than not to respond, irrespective of the task (see, e.g., Mordkoff, Yantis & Egeth, 1990, for similar results). No response bias can account for the present results.

At first sight the results of Experiment 2 are much like the results of Experiment 1. Yet, there are some differences. First, there was a significant effect of the number of green elements on target present RT. It is unclear how to interpret this finding. Second, responses were faster in Experiment 2, whereas no important decrease in error rate has been observed (in the present Experiment an overall error rate of 5.7% compared with 6.3% respectively in Experiment 1). Note that accuracy and speed can be traded. The maximum error rate that subjects accept determines their response latencies. Third, target absent response latencies had decreased relatively little compared to the decrease of the target present latencies. This implies that part of the results of Experiment 1 may be accounted by a response bias towards responding target absent. Yet, since the interesting phenomena in the results of Experiment 1 (i.e., target absent slopes were shallower than target present results and target absent responses were in some conditions faster than target present responses and in other conditions slower) can be found in the present results as well, this response bias could not have caused these effects.

3.3 Discussion: Target search and distractor matching

The results of Experiment 2 clearly show that a response bias (or response competition effects) may not have caused the important aspects of the results that were obtained in Experiment 1: shallower target absent slopes and, only in some conditions, fast absents. In the Introduction of this report it has been argued that this pattern of results could not be explained by a one-process search theory. In the following sections a two-process account is proposed for the present findings. Subsequently this account will be tested in Experiments 3 and 4.

It is hypothesized that, in the present Experiments, the target absent results and target present results are predominantly determined by the outcomes of different processes. In the following these processes will be referred to as 'target search' and 'distractor matching', respectively. Target search is the well-known serial, self-terminating search process (that usually results in the 1:2 ratio of target present and target absent slopes). All potential targets (in the present conditions: all red elements) are scanned one by one until a target is found. This process is generally accepted to account for the results of many conjunction search tasks and some feature search tasks (i.e., if target and distractors are very similar, see Duncan & Humphreys, 1989). Distractor matching is a (weak) parallel matching process. The potential targets (here: red elements) are matched in parallel over the entire visual field and, if all potential targets are the same (share the same orientation) this implies that no target is present (since a target would have disturbed the "sameness" of the red elements) and the subject responds accordingly.

Thus, it is hypothesized that the fast absent responses are the result of a weak parallel matching process that can be used for responding "target absent" when there is a certain level of "sameness" among the red elements. When all red elements have the same orientation the distractor matching process *might* enable responding "target absent". Yet, the absence of a "sameness"-signal can not be used for responding "target present". The distractor matching process is weak and can be easily disturbed, so that occasionally no "sameness"-signal is received although all target color elements are identical. As a consequence, serial, self-terminating search is always necessary at the absence of a "sameness"-signal in order to distinguish between target present trials and target absent trials.

The notion that different processes determine target present and target absent response has been used previously to account for inconsistencies between target present and target absent results in feature search (see Treisman, Sykes & Gelade, 1977; Quinlan & Humphreys, 1987) and to account for inconsistencies between the results of "same" and "different" trials in same-different tasks (e.g., Bamber, 1969).

Previously reported research also provides external support for the idea that distractor matching may be fast. In a typical same-different task subjects are to judge whether some stimuli (usually two) are different from each other or whether they are the same. In general 'same'-responses are faster than 'different'-responses (the fast same-effect; see, e.g., Kwak, Dagenbach & Egeth, 1990; Farell, 1985). This finding has not yet been convincingly accounted for (see Theeuwes, 1991; Krueger, 1978; Proctor, 1981). Yet, distractor matching can be regarded a same-different task: subjects are to respond 'present' if one of the investigated elements (i.e., the elements in the target color) is different from the rest, and 'absent' if they are all identical. In analogy to the fast-same effect, for target absent trials this process would be expected to reach its conclusion faster than for target present trials, which is in line with our account of the present results.

How does the pattern of results of Experiments 1 and 2 (and of Theeuwes et al., 1993) fit into the present account? As far as target present trials are concerned there is nothing new: the elements in the color of the target are selected (see Theeuwes et al) and then searched one by one (the target search process). Consequently, RTs increase with the number of red elements, and are independent of the number of green ones. On target absent trials the majority of results reflect the outcome of the distractor matching process: some 'sameness'-signal is generated. Distractor matching occurs in parallel over the red elements in the entire visual field and is affected by the number of green elements, either because the distractor matching process itself is disturbed by the presence of green elements among the red ones, or because green elements may occasionally increase the level of noise so that distractor matching has a larger chance to fail, and the potential targets have to be searched more often. Analogously, the effect of the number of red elements may indicate that the distractor matching process behaves as a limited-capacity parallel process (see Townshend 1971, 1972, 1990 on the identifiability of serial and parallel processes; cf. Pashler's (1987) account that was outlined in the introduction) or, again, that target search is needed more frequently.

Since distractor matching is hard to imagine in case of only one red element, the finding that in conditions with only one red element target present results are always faster than target absent results is no surprise. This type of trials will be omitted in subsequent experiments.

The account that is presented above is to a large extent based on the present findings alone, and admittedly post-hoc, so that it is necessary to obtain additional evidence. Of course, the critical aspects of the present model are the color-based subset-selective search that was demonstrated by Theeuwes et al. (1993; see also Egeth et al., 1984) and the distractor matching process, that also is only supported by the experiments of Theeuwes et al. In the rest of this study it is attempted to show that target absent data are no longer fast if distractor matching is made impossible. The present hypothesis predicts that data under

such conditions reflect pure target search. In addition, the present hypothesis also predicts that the color-based search selectivity will not be affected by a manipulation of the stimulus material that does not affect colors.

In Experiment 3 these predictions are tested. Distractor matching is made difficult by randomly varying the tilt of the red line segments. It is then expected that the target present : target absent slope ratio increases with the variation in orientation of the red distractor elements.

4 EXPERIMENT 3

In Experiment 3 the target search and distractor matching account of the results of Experiments 1 and 2 is tested. The present experiment is similar to Experiment 1, except for that red distractor elements are (randomly) tilted between 20° and 40°, instead of the fixed 20° tilt in Experiment 1. It is hypothesized that this modification selectively affects distractor matching, so that the target present : target absent slope ratio increases compared to when all red distractors are always tilted 20°. There was one minor change in the procedure. Since instructing subjects to search for the elements in the target color theoretically may have caused the color-selective search, in the Experiments 3 and 4 subjects have not been instructed explicitly to search among elements in the color of the target.

4.1 Method

Subjects

Eight right-handed subjects, ranging in age from 18 to 25 years participated as paid volunteers.

Apparatus

The apparatus was similar to that in the previous experiments.

Task and stimuli

The task was the same as in Experiment 1. Rather than explicitly instructing subjects to search only among the red elements as in the previous experiments, subjects were only instructed to search for a red, vertical line segment. In addition, in the present experiment in one condition (the heterogeneous condition) red distractor elements were tilted between 20° and 40° to the right of vertical. Within each trial each red element was individually assigned randomly a tilt of between 20° and 40°. As a result, stimulus displays showed a varying

degree of differences in the tilt of the red distractor elements. In the other condition (the homogeneous condition) all red distractors were tilted 20°. The tilt of the red distractors was a within-subjects variable. Trial types were blocked. In order to restrict the number of cells, only displays with 2, 4 or 6 red elements and 2, 4 or 6 green elements were used in the present experiment.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of, respectively, .28/.34 and a luminance of 54 cd/m^2. The target and distractors were presented in red (.62/.36; 8.7 cd/m^2) and green (.31/60.; 8.7 cd/m^2), with a dark grey background (.32/.37; 0.8 cd/m^2).

Procedure

The procedure was generally similar to the procedure in the previous experiments. A block consisted of 3 (2, 4 or 6 red items) × 3 (2, 4 or 6 green items) × 2 (target present or target absent) × 20 (replicas) = 360 trials. Each subject received four blocks of stimuli (two block in the homogeneous condition and two blocks in the heterogeneous condition), that is a total of 1440 trials. Half of the subjects started with the two blocks in the homogeneous condition, whereas the other half of the subjects started with the two blocks in the heterogeneous condition. In each condition subjects received one practice block, consisting of 360 trials, before the first experimental block, with feedback after every 90 trials. There was a 30 minute break between the two conditions. After every 90 trials subjects received feedback and were provided with the opportunity for a break.

4.2 Results

Response times longer than 1500 ms were counted as errors, which led to a loss of 0.87% of the trials.

Fig. 9 shows the results of the homogeneous condition. In Fig. 9 mean RTs and error percentages are plotted against the number of displayed green elements, separately for target present (Panel A) and for target absent trials (Panel B). For target present trials, there was a significant main effect of the number of red elements [$F(2,14) = 25.3$, $p < 0.01$] but not of the number of green elements. For target absent trials, there was a significant effect of the number of green elements [$F(2,14) = 35.4$, $p < 0.01$] and of the number of red elements [$F(2,14) = 22.0$, $p < 0.01$].

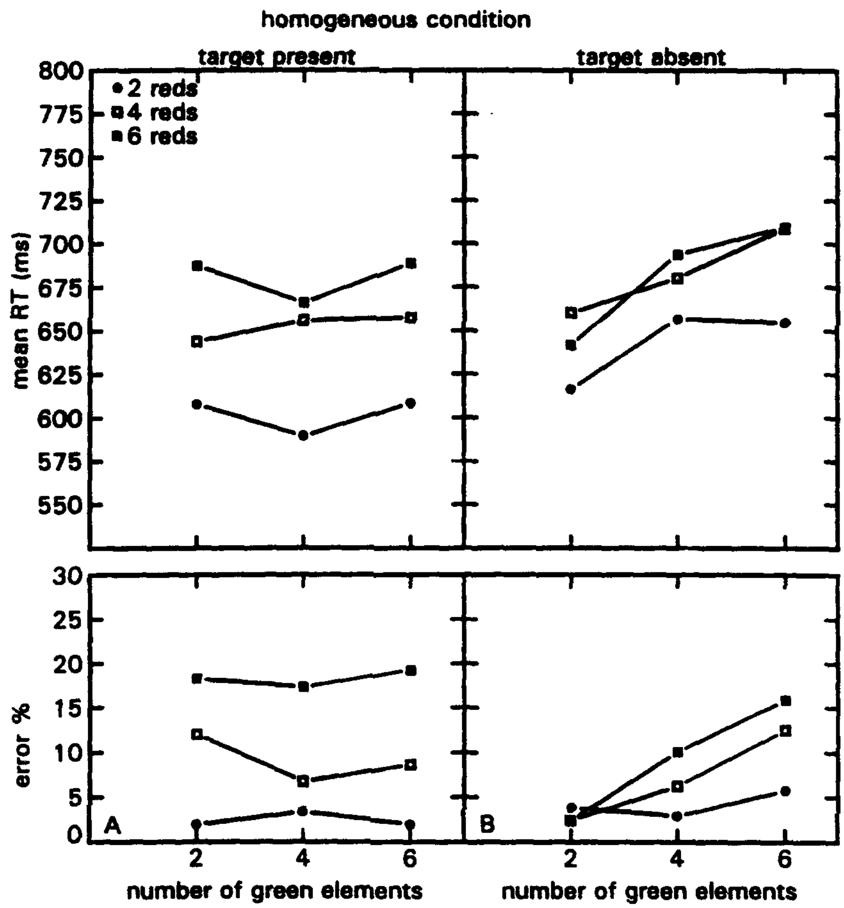

Fig. 9 Experiment 3: Homogeneous condition. Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

Fig. 10 shows the results of the heterogeneous condition. In Fig. 10, like in Fig. 9, RTs and error percentages are plotted against the number of displayed green elements, separately for target present (Panel A) and for target absent trials (Panel B). For target present trials, there was a significant main effect of the number of red elements [$F(2,14) = 53.1$, $p < 0.01$], but not of the number of green elements. For target absent trials, there was a significant main effect of the number of green elements [$F(2,14) = 9.8$, $p < 0.01$] and of the number of red elements [$F(2,14) = 33.9$, $p < 0.01$].

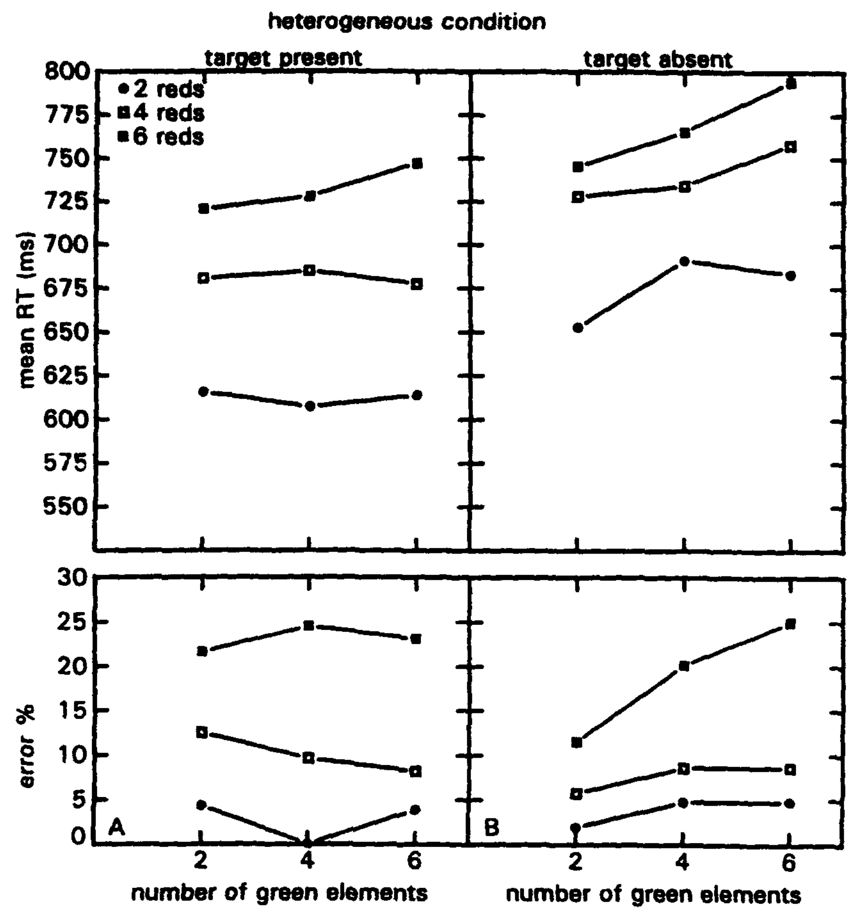

Fig. 10 Experiment 3: Heterogeneous condition. Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

In Figs 11 and 12 the data of Figs 9 and 10 are presented in an different way. Mean RTs and error percentages are plotted against the number of red elements, separately for each number of green elements, both for target present (Panel A) and for target absent trials (Panel B). To determine the slopes of the RT functions presented in Figs 9, 10, 11 and 12 linear regression analyses were performed on the mean RTs per subject. The slopes and intercepts are shown in Table III. T-tests were performed to test whether the slopes were significantly different from zero. The results of these tests are shown in Table III as well.

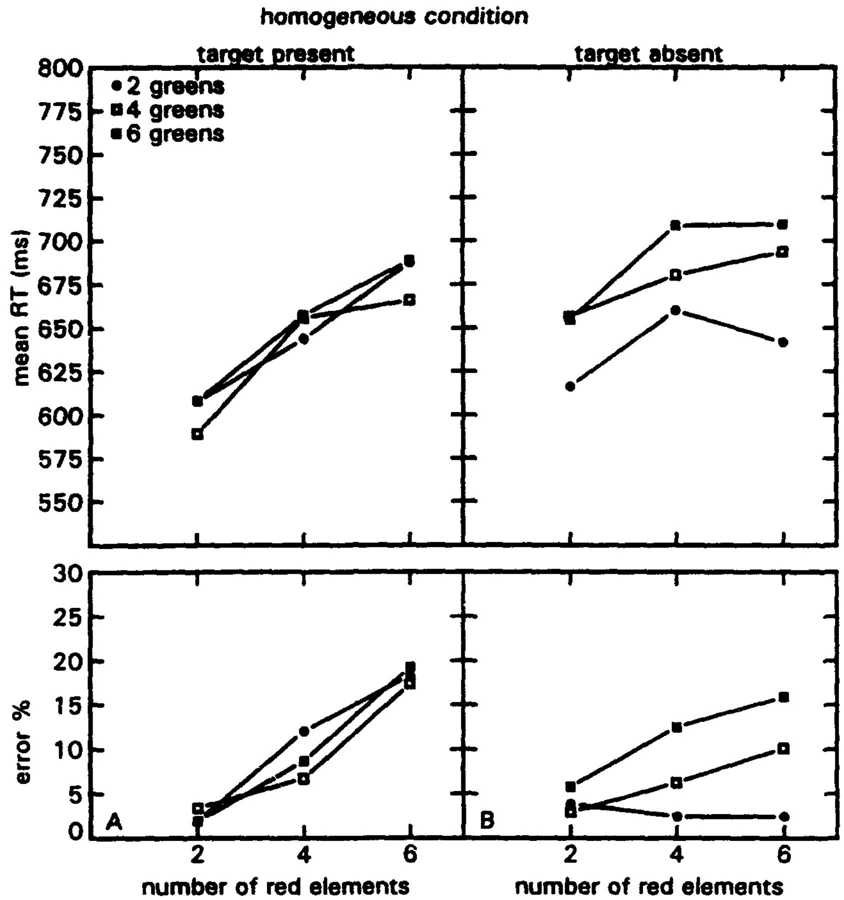

Fig. 11 Experiment 3: Homogeneous condition. Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

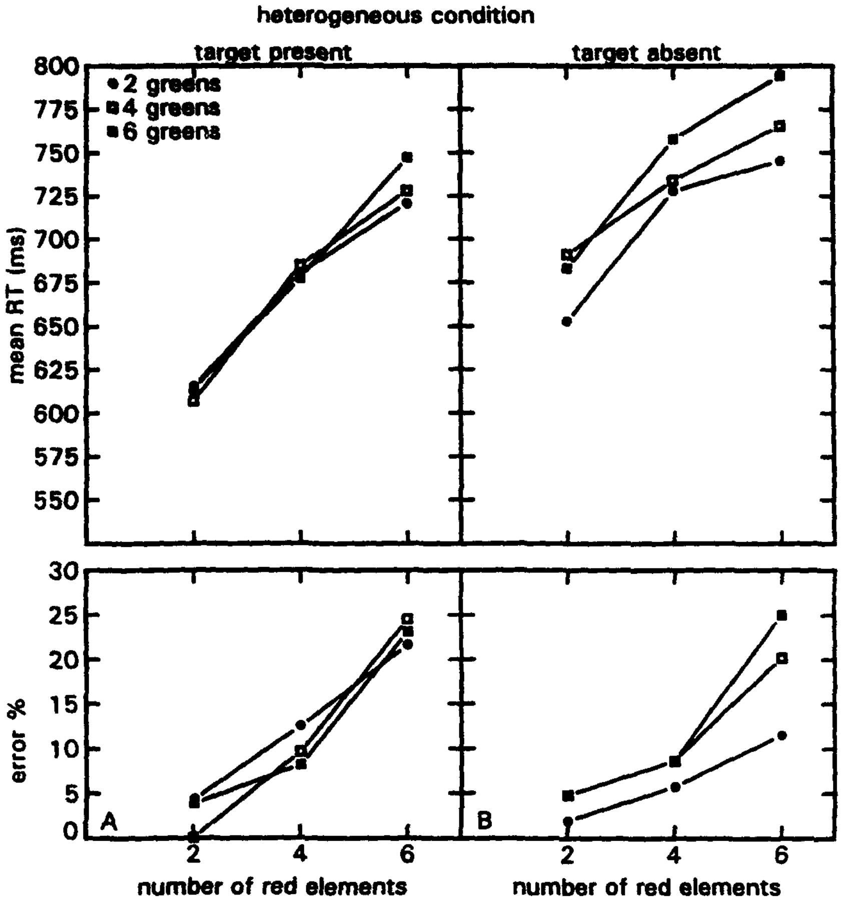

Fig. 12 Experiment 3: Heterogeneous condition. Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

Table III Slopes and intercepts corresponding to the RT functions in Figs 9 to 12.

	intercept [ms]	slope [ms/ element]	t(7) =	p <		intercept [ms]	slope [ms/ element]	t(7) =	p <
homogeneous condition					**heterogeneous condition**				
RT as a function of # green elements, separately for each # reds (see Fig. 9)					*RT as a function of # green elements, separately for each # reds (see Fig. 10)*				
target present					target present				
2 red elements	601.7	0.13	0.036	n.s.	2 red elements	611.2	0.09	0.064	n.s.
4 red elements	637.5	3.82	0.901	n.s.	4 red elements	689.0	-1.15	0.254	n.s.
6 red elements	691.8	-1.11	0.254	n.s.	6 red elements	714.2	4.53	1.673	n.s.
target absent					target absent				
2 red elements	605.6	9.21	2.639	0.05	2 red elements	644.8	7.58	2.714	0.05
4 red elements	631.4	13.32	3.948	0.01	4 red elements	709.7	8.36	1.883	n.s.
6 red elements	614.7	17.53	6.285	0.01	6 red elements	721.7	12.33	3.892	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 11)					*RT as a function of # red elements, separately for each # greens (see Fig. 12)*				
target present					target present				
2 green elements	560.2	22.20	4.366	0.01	2 green elements	560.3	28.85	6.182	0.01
4 green elements	557.7	20.74	5.728	0.01	4 green elements	558.3	28.49	8.613	0.01
6 green elements	567.6	21.21	4.738	0.01	6 green elements	547.1	33.29	6.803	0.01
target absent					target absent				
2 green elements	613.8	6.49	3.708	0.01	2 green elements	613.8	24.03	6.240	0.01
4 green elements	637.2	10.45	3.362	0.01	4 green elements	655.3	19.14	5.587	0.01
6 green elements	634.0	14.80	4.145	0.01	6 green elements	632.5	28.78	6.194	0.01

In the homogeneous condition, for target present trials there was a significant main effect on error rate of the number of red elements [$F(2,14) = 26.7$, $p < 0.01$], but not of the number of green elements. For target absent trials there was a significant main effect of the number of green elements [$F(2,14) = 25.7$, $p < 0.01$], but not of the number of red elements. The interaction between red and green elements was significant [$F(2,14) = 2.9$, $p < 0.05$]: the effect of the number of green elements increased with the number of red elements.

In the heterogeneous condition, for target present trials there was a significant main effect on error rate of the number of red elements [$F(2,14) = 36.7$, $p < 0.01$] but not of the number of green elements. For target absent trials there were main effects on error rate of both the number of red elements [$F(2,14) = 6.8$, $p < 0.01$] and of the number of green elements [$F(2,14) = 17.8$, $p < 0.01$].

Since all significant effects of error rate mimic effects on response latency, the significance of effects on RT can not be the result of a speed-accuracy trade-off.

4.3 Discussion

The results of Experiment 3 indicate that the introduction of variation in the orientations of the red distractor elements has made the distractor matching process more difficult. Compared to without red distractor variation the slopes of target present RT functions (assumed to reflect the target search process) increased, but the ratio of target present and absent slopes also had increased with red distractor variation. Note that the degree of this increase is not very large.

This finding may indicate that on some trials subjects have had difficulties with distractor matching, while on other trials they did not have any trouble. Support for this suggestion may be derived from a closer look at the way the tilt of the red elements was randomized in the present experiment. Each element was individually assigned a random tilt between 20° and 40°. As a consequence, the amount of within-display variation differed from trial to trial. If, for instance, all red distractor elements were tilted between 25° and 35°, the distractor matching process may not have been disturbed enough to make it ineffective. The increase in slope ratio may than be attributed to a subset of trials, in which variation was large enough to be disturbing. If this is correct, it indicates that the occurrence of distractor-matching is not strategy-dependent. If the level of within-display variation of the orientation of the red distractor elements is controlled more accurately, large effects are expected to be found.

In Experiment 4 there were only two levels of variation: no variation and maximal variation. Again, it was expected that distractor matching would be dominating target absent results in the first condition, and that target absent results in the latter condition would reflect target search. Condition is a within-

block variable in Experiment 4. The results of Experiment 4 should give insight in the extent to which the distractor matching process is inhibited (or made impossible) when red distractors are different within a stimulus field. Theoretically, the results of this type of trials are expected to fit into the 1:2 ratio of target present and target absent slopes that is obtained through the serial, self-terminating target search process.

Since the results of Experiment 3 show that the color-selective search is not critically instruction-dependent, in Experiment 4 subjects were again not instructed to search among elements in the color of the target.

5 EXPERIMENT 4

In Experiment 4 stimulus displays with and without within-display orientation variation among the red distractors are intermingled within-blocks. In half of the trials (the homogeneous condition) the red distractor elements were tilted either all -25° or all +25°; all red distractor orientations were identical. In the other half of the trials (the heterogeneous condition) half of the red distractors was tilted -25° and the other half +25°. In this way the within-display variation among the red distractor elements was maximized. It was expected that without within-display variation, the pattern of the target absent results of Experiment 1 would be replicated, whereas with within-display variation results would purely reflect a target search process, showing a 1:2 ratio of target present and target absent search function slopes.

5.1 Method

Subjects

Eight right-handed subjects. ranging in age from 18 to 25 years participated as paid volunteers.

Apparatus

The apparatus was similar to in the previous experiments.

Task and stimuli

The task was the same as in Experiment 3. Additionally, in the present experiment the red distractor elements were either a) all tilted -25° (i.e., 25° left from vertical), or all tilted +25° (the homogeneous condition) or b) half were tilted -25° and the other half tilted +25° (the inhomogeneous condition).

Color Specifications

The same colors as in Experiment 3 were used.

Procedure

The procedure was generally similar to the procedure in the previous experiments. A block consisted of 3 (2, 4 or 6 red elements) × 3 (2, 4 or 6 green elements) × 2 (target present or target absent) × 2 (homogeneous or inhomogeneous red distractors) × 20 (replicas) = 720 trials. Each subject received two blocks of stimuli, that is a total of 1440 trials. Before the first experimental block subjects received one practice block, consisting of 720 trials, with feedback after every 90 trials. There was a 30 minute break between two blocks. After every 90 trials subjects received feedback and were provided with the opportunity for a break.

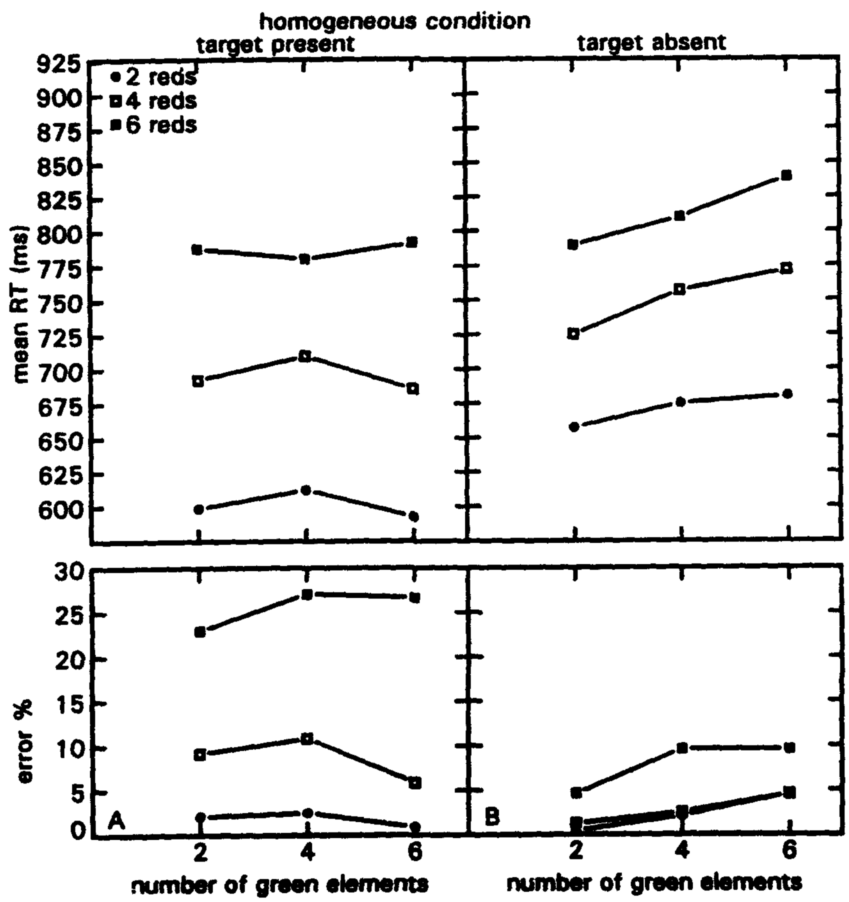

Fig. 13 Experiment 4: Homogeneous condition. Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

5.2 Results

Response times longer than 1500 ms were counted as errors, which led to the loss of 0.42% of the trials. Fig. 13 shows the results of the homogeneous condition. In Fig. 13 mean RTs and error percentages are plotted against the number of displayed green elements, separately for target present (Panel A) and target absent trials (Panel B).

For target present trials there was a significant effect of the number of red elements [$F(2,14) = 41.7$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was not significant. For target absent trials there were both effects of the number of red elements [$F(2,14) = 40.2$, $p < 0.01$] and of the number of green elements [$F(2,14) = 21.5$, $p < 0.01$]. The interaction between the numbers of red and green elements was not significant.

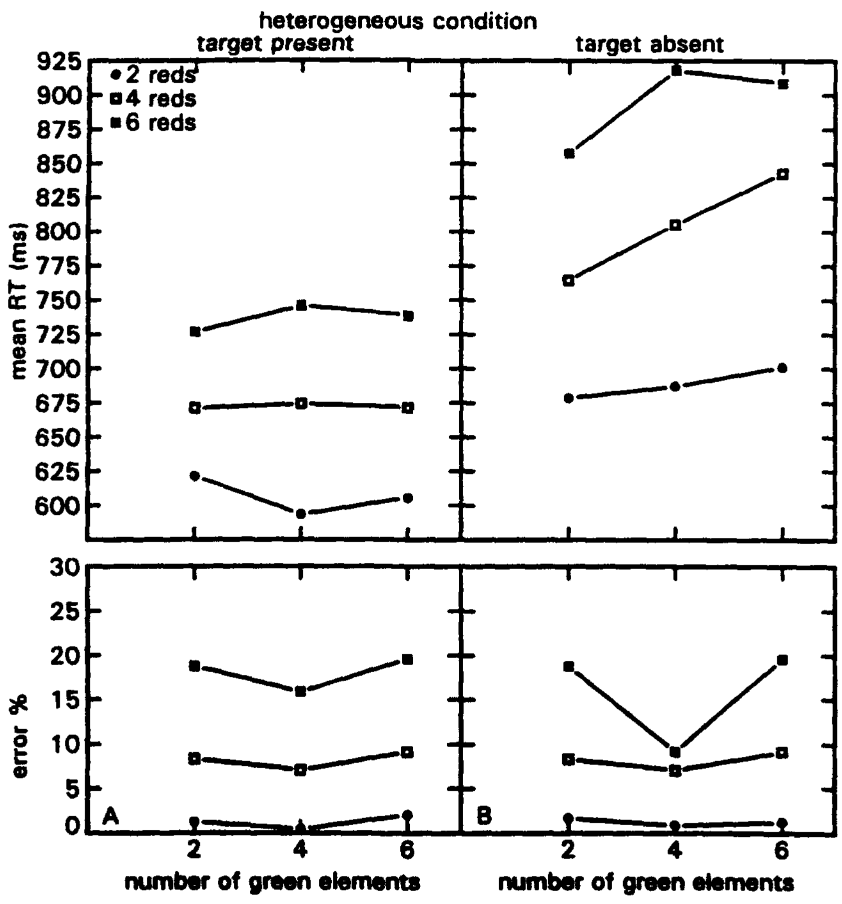

Fig. 14 Experiment 4: Heterogeneous condition. Mean RTs and error percentages as a function of the number of displayed green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

Fig. 14 shows the results of the heterogeneous condition. In Fig. 14, like in Fig. 13, RTs and error percentages are plotted against the number of displayed green elements, separately for target present (Panel A) and for target absent trials (Panel B). For target present trials, there was a significant effect of the number of red elements [$F(2,14) = 57.5$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was not significant. For target absent trials there were both effects of the number of red elements [$F(2,14) = 76.7$, $p < 0.01$] and of the number of green trials [$F(2,14) = 19.6$, $p < 0.01$]. The numbers of red and green elements had a significant interaction effect as well [$F(4,28) = 3.36$, $p < 0.05$]. The effect of the number of elements in one color increased with the number of elements in the other color.

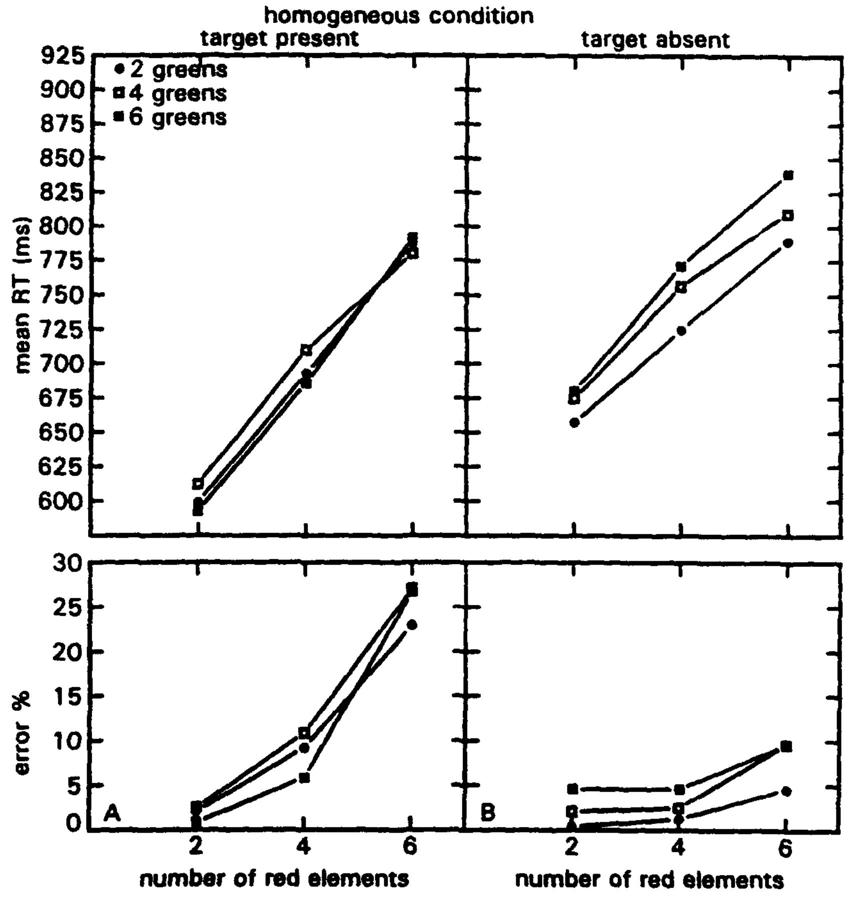

Fig. 15 Experiment 4: Homogeneous condition. Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

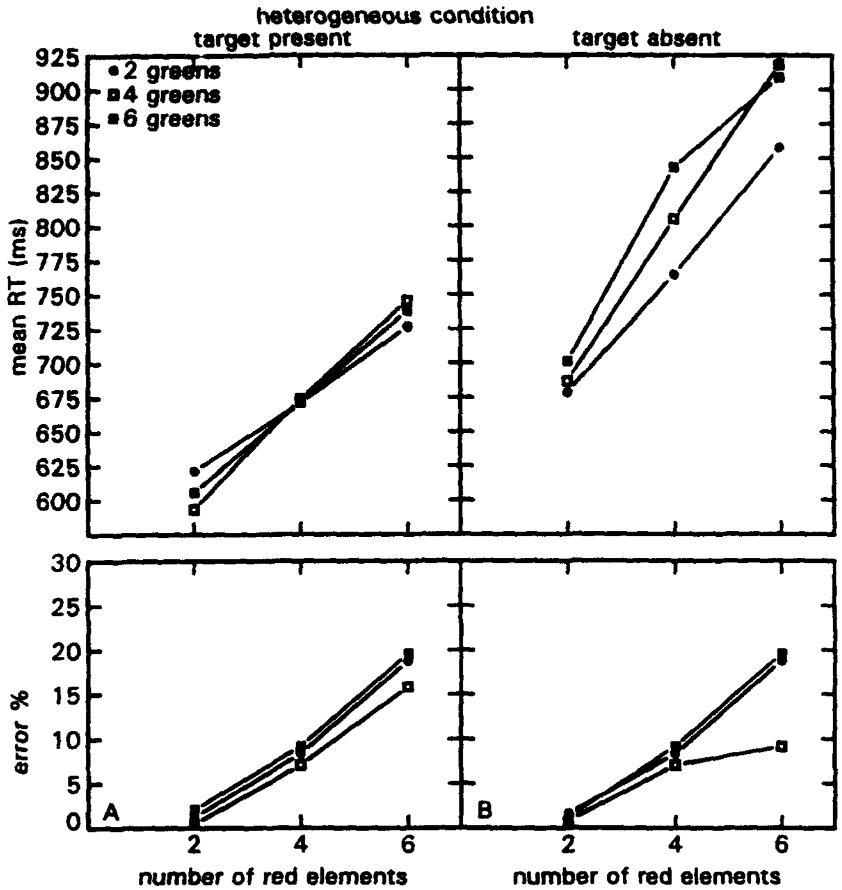

Fig. 16 Experiment 4: Heterogeneous condition. Mean RTs and error percentages as a function of the number of displayed red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

In Figs 15 and 16 the data of Figs 13 and 14 are presented in an different way. Mean RTs and error percentages are plotted against the number of red elements, separately for each number of green elements, both for target present (Panel A) and for target absent trials (Panel B). To determine the slopes of the RT functions presented in Figs 13, 14, 15 and 16 linear regression analyses were performed on the mean RTs per subject. The slopes and intercepts are shown in Table IV.

Table IV Slopes and intercepts corresponding to the RT functions in Figs 13 to 16.

	intercept [ms]	slope [ms/element]	t(7) =	p <		intercept [ms]	slope [ms/element]	t(7) =	p <
homogeneous condition					**heterogeneous condition**				
RT as a function of # green elements, separately for each # reds (see Fig. 13)					*RT as a function of # green elements, separately for each # reds (see Fig. 14)*				
target present					**target present**				
2 red elements	607.4	-1.58	0.668	n.s.	2 red elements	622.3	-3.89	1.123	n.s.
4 red elements	703.0	-1.73	1.048	n.s.	4 red elements	671.9	0.11	0.051	n.s.
6 red elements	682.3	1.04	0.216	n.s.	6 red elements	725.3	2.92	1.365	n.s.
target absent					**target absent**				
2 red elements	647.9	5.77	2.987	0.05	2 red elements	666.6	5.62	2.734	0.05
4 red elements	704.4	11.63	3.958	0.01	4 red elements	725.6	19.63	5.164	0.01
6 red elements	762.9	12.46	3.841	0.01	6 red elements	843.5	12.78	2.731	0.05
RT as a function of # red elements, separately for each # greens (see Fig. 15)					*RT as a function of # red elements, separately for each # greens (see Fig. 16)*				
target present					**target present**				
2 green elements	504.2	47.21	9.222	0.01	2 green elements	567.5	26.39	5.070	0.01
4 green elements	532.7	41.98	4.642	0.01	4 green elements	518.7	38.10	7.681	0.01
6 green elements	490.7	49.83	8.105	0.01	6 green elements	539.1	33.20	12.79	0.01
target absent					**target absent**				
2 green elements	591.9	32.99	7.756	0.01	2 green elements	588.3	44.65	6.835	0.01
4 green elements	612.3	33.68	6.158	0.01	4 green elements	572.7	57.67	8.648	0.01
6 green elements	604.9	39.68	6.298	0.01	6 green elements	610.4	51.80	13.47	0.01

In the homogeneous condition, for target present trials there was a significant effect on error rate of the number of red elements [$F(2,14) = 41.7$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was not significant. For target absent trials there were main effects of both the number of green elements [$F(2,14) = 6.5$, $p < 0.05$] and of the number of red elements [$F(2,14) = 7.5$, $p < 0.01$]. The interaction between the numbers of red and green elements was not significant.

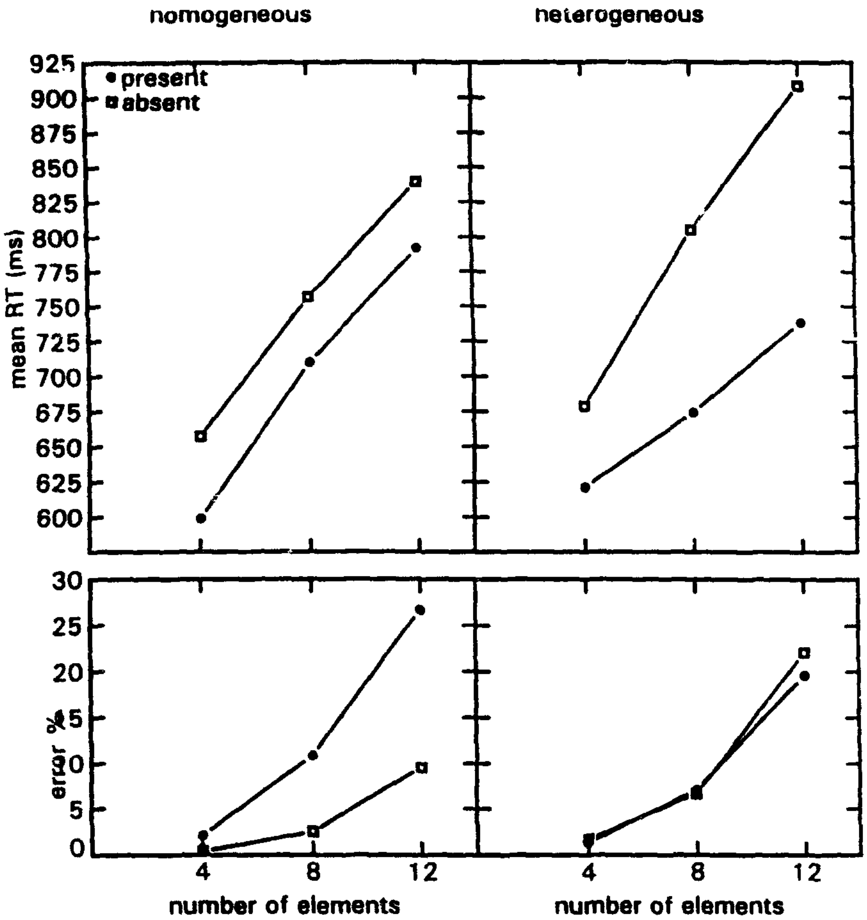

Fig. 17 Experiment 4: Mean RTs and error percentages of trials with an equal number of red and green elements as a function of display size, both for the homogeneous condition and for the heterogeneous condition, separately for target present and target absent trials.

In the heterogeneous condition, for target present trials there was a significant effect of the number of red elements [$F(2,14) = 33.2$, $p < 0.01$] but not of the number of green elements. The interaction effect between the numbers of red and green elements was not significant. For target absent trials there were main effects on error rate of both the number of red elements [$F(2,14) = 14.8$, $p < 0.01$] and of the number of green elements [$F(2,14) = 6.7$, $p < 0.01$]. The

interaction effect of the numbers of red and green elements was significant as well. The effect of the number of elements in one color increased with the number of elements in the other color.

Fig. 17 shows the RTs and error percentages of the homogeneous and heterogeneous conditions as a function of the numbers of elements for trials with equal numbers of red and green elements. For the homogeneous condition the slope of the target present function was 24.1 ms/element [$t(7)$ = 8.551] and the slope of the target absent function 22.7 ms/element [$t(7)$ = 8.584], giving a slope ratio of close to 1:1 (1:0.94). For the inhomogeneous condition, the target present search function slope was 14.7 ms/element [$t(7)$ = 5.738]; the target absent search function slope was 28.7 ms/element [$t(7)$ = 14.01] rendering a slope ratio of almost 1:2 (1:1.96).

Since all significant effects on error rate mimic effects on response latency, the significance of effects on RT can not be the result of a speed-accuracy trade-off.

5.3 Discussion

The results of Experiment 4 are in line with the two-process conjunction search account that assumes parallel operation of the target search and distractor matching processes.

In the homogeneous condition the stimuli are comparable to the stimuli that were used in Experiments 1 and 2, and so are the results: for target present trials there only is an effect of the number of red elements, not of the number of green ones. Also, target absent slopes are smaller than target present slopes (with RT as a function of the number of reds). Target present search slopes have increased as expected since in the present experiment it is harder to discriminate the target from the distractors (see Duncan & Humphreys, 1989; 1992).

In the inhomogeneous condition results are more in line with the traditional findings. The pattern of target present results is not very different compared to the homogeneous condition. Yet, this time target absent slopes are larger than target present slopes. So, apparently, inhibiting the distractor matching process has been successful and has led to the predicted results.

If the distractor matching process really is inhibited, one would expect to find a 1:2 ratio of target present and target absent slopes if RT as a function of the number of red elements is considered. The present results were slightly different: ratios were about 1:1.6. However, when only considering trials with equal numbers of red and green elements the slope ratio would increase to 1.96 (in the homogeneous condition the 1:1 ratio of the previous experiments would be found again). In other words, it is to be expected that in the heterogeneous condition,

when only presenting stimuli with equal numbers of elements of both distractor types, one would obtain the standard 1:2 slope ratio.

Obviously, in the present experiment the difference between 1.6 and 1.96 can be ascribed to the (relatively small) effect of the number of green elements. To these issues will be returned in the General Discussion section.

Finally, the results of Experiment 4 convincingly show that the subset-selective search for on target present trials is not dependent on the distractor matching process that caused the fast absents. Since both in the homogeneous- and in the inhomogeneous conditions of the present experiment target present results only depended on the number of displayed red elements, it might be reasonable to expect that subset-selective search occurs in other conjunction search tasks as well. It is unclear to what extent this is the case. Further research is needed to assess the range of search selectivity, as well as to investigate in what conditions the distractor matching process can be or will be used. Again, to this issue will be returned in the General Discussion section.

6 GENERAL DISCUSSION

The results of the present series of experiments can be summarized as follows:

1 As long as the elements in the color of the target are sufficiently alike (and possibly as long as the stimuli are not too complex) search latencies reflect the operation of two different search processes. Target present responses are determined by the target search process, whereas most target absent results are determined by the distractor matching process. Still, since the distractor matching process is easily disturbed, some of the target absent trials still need to be based on the target search process (all experiments).

2 Due to distractor matching target absent responses may be relatively fast, and target absent search function slopes relatively flat. These findings are not the result of response competition effects (Experiment 2).

3 Distractor matching breaks down if the distractor elements in the color of the target differ sufficiently from each other (Experiments 3 and 4).

4 Subset-selective search does not depend on the occurrence of distractor matching (Experiment 4).

5 Independently varying the numbers of elements reveals aspects of conjunction search that would have remained unobserved otherwise. The present procedure has proven to be a useful diagnostic in visual (conjunction) search (all experiments).

The possibility of subset-selective search was already established by Theeuwes et al. (1993; see also Egeth et al., 1984). Additionally, the present study shows that subset selectivity is perfectly compatible with standard conjunction search results, and that is it not dependent on the occurrence of distractor matching. Therefore, the claim that current visual search theories should account for subset-selective search is even stronger after the present results (See Theeuwes et al., 1993, for a more elaborate discussion). It should be realized that both subset-selective search and distractor matching are likely to have occurred in previously reported conjunction search experiments. Because these experiments did not use the appropriate conditions, the existence of these processes was not noticed. Only due to the different methodology that was used in the present study and in Theeuwes et al., 1993, by independently varying the numbers of both distractor types, subset-selective search and distractor matching could be detected. Yet, on the basis of the present results it is unclear to what extent the present findings can be generalized.

As to selective search, Egeth et al. (1984) showed that, apart from selective search among elements in the target color, subjects were also able to search selectively among elements of the same form of the target, although less efficient. It is reasonable to expect that selectivity that is based on a given dimension will be easier when stimulus groups differ more in that dimension, but there is no a priori reason why only the color dimension could be used for selective search. The present results are therefore expected to generalize to other search tasks. It is feasible that selective search breaks down with large stimulus numbers (see for instance Trick & Pylyshyn, 1993), or when the stimulus groups are highly similar.

The present results showed that the similarity of the relevant distractors is of crucial importance for the efficiency of the distractor matching process. The number of elements that is involved might also play an important role, since elements are supposedly matched in parallel (see, e.g., Trick & Pylyshyn, 1993 for an example of a parallel process over a limited number of elements). The number of elements may be more of effect when stimuli are relatively complex. Next, complexity itself might be counteracting the matching process: in the present studies only simple stimuli were used that easily could be matched.

From the present study it follows that different perceptual processes can be used for target present and absent responses. Similar suggestions have been made by Bamber (1969) for same-different tasks and by Treisman et al. (1977; see also Quinlan & Humphreys, 1987) for feature search. In all of these examples one of the perceptual processes was performed in parallel over the entire stimulus set, like the distractor matching process in the present experiments.

As stated in the introduction, Pashler (1987; see also Houck & Hoffman, 1986; Duncan & Humphreys, 1989: experiment 3) found 1:1 target present : target absent search function slopes for small display sizes. Treisman (1991; Treisman

& Gelade, 1980) amongst others has found 1:2 target present : target absent slope ratios. Pashler has suggested that this difference in slope ratios stems from a clump-wise search strategy: subjects search the display in sets of (for instance) about eight elements. Search within clumps then is supposed to be parallel (which may explain the 1:1 search ratio), search between clumps is serial. Remember that increasing RTs with the number of search elements by no means is specific for serial search processes (Townshend 1971, 1972, 1990), so this suggestion seems not a priori unreasonable. Yet, in the light of the present results, it could be argued that these differences between target present to target absent slope ratios in conjunction search experiments might be related to the occurrence of distractor matching, like in the present experiments. If in the present study search function slopes are plotted against the number of displayed elements (the display size) either 1:1 or 1:2 slope ratios are obtained. Most of the present experiments yield 1:1 slope ratios, only in the heterogeneous condition of Experiment 4 (where distractor matching was made unattractive or impossible) a 1:2 slope ratio was observed. Pashler's observation that the relation between target present and target absent results depends on display size is in line with this account: distractor matching might have caused relatively fast absents in Pashler's experiments as well. Note that, as suggested above, display size limitations on the distractor matching process are not unlikely (although Pashler's findings also might reflect the use of directed refixations while scanning the display to find the target).

A related concern is that the 1:2 ratio that emerges when covarying the numbers of distractor types does not necessarily simply reflect serial self-terminating search among the red elements. The 1:2 ratio is predominantly the result of the 1:1.6 ratio of the red-element search functions. In addition, the number of green elements still has an effect on target absent trials. So the observed search function slope ratio of 1:2 can not be straightforwardly interpreted as serial, self-terminating search. It might be interpreted as showing that the distractor matching process has not been fully excluded in conditions where the 1:2 slope ratio was found. Another possibility is that the target search process is also faster in case of target absent trials (due to a decrease in noise, for instance; note that target present slopes are still smaller because on the average only half of the relevant elements have to be scanned), and that some additional effect of the green elements occurs on target absent trials, like an occasional salient green element (neighboring red ones) that is incidently selected after all the red ones have been searched. The present data are insufficient to conclude on these issues.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

In search for a conjunction of color and orientation, Theeuwes, Kaptein and Van der Heijden (1993) obtained target absent responses that were in some conditions faster and in other conditions slower than target present responses. In addition, target absent search function slopes were shallower than target present slopes. These findings cannot be explained by present conjunction search theories. Since in the same study Theeuwes et al. demonstrated subset-selectivity in conjunction search, the interdependence of the fast absent responses and subset-selective search needed to be assessed. The present study shows that subset-selective search is independent of the occurrence of fast absent responses. Experiment 1 replicated the findings of Theeuwes et al. (1993). Experiment 2 showed that the fast absents were not the result of a response bias. The results of Experiments 3 and 4 showed that the fast absents can be explained by a weak, parallel distractor matching process that enables responding "target absent" if all relevant distractor elements are similar. Since this process is easily disturbed, the absence of a "sameness"-signal can not be used for "target present"-decisions. It is argued that both subset-selective search and distractor matching may have unnotedly occurred in previously reported experiments.

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